Light Higgs Scenario in BMSSM and LEP Precision Data

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Abstract

In this Letter we consider very light Higgs fields in BMSSM(Beyond MSSM). The spectrum below TeV scale is the same as the MSSM but the Higgs potential is modified and is well described in terms of effective dimension five and six operators. A correction from the BMSSM operators allows us to consider new parameter space of Higgs sector which is not allowed in the MSSM. It can be regarded as a constrained version of general 2 Higgs doublet model (2HDM) as long as Higgs sector is concerned. We focus on the possibility that CP odd Higgs (A) mass is about 7 or 8 GeV and charged Higgs mass is comparable to W mass. At the same time one of the CP even Higgs (h) is light enough such that h and A production at the Z pole is kinematically allowed. The tension between forward backward asymmetry of bottom quark $A^b_{\rm FB}$ measured at LEP and the Standard Model prediction can be ameliorated if bottom quark pair produced from light CP even Higgs is taken into account.

I. INTRODUCTION

The Standard Model (SM) has been almost completed by the discovery of top quark at the Tevatron and the only missing ingredient is the Higgs. LEP I/II experiments were done mainly to discover Higgs but without success up to Higgs mass 114 GeV [1]. Though it rules out small part of the parameter space for the SM Higgs sector, it rules out most of natural parameter space for the minimal supersymmetric standard model (MSSM).

In the MSSM, the quartic coupling of Higgs in the potential is determined from measured gauge couplings and the light CP even Higgs mass has an upper bound of about 120 GeV (which can be 130 or 135 GeV if stop mixing is maximal) [2] [3]. However, this upper bound is achieved only when the stop mass is as heavy as 1 TeV which makes it difficult to understand the weak scale out of it. This 'little hierarchy problem' in the MSSM has been considered seriously for recent several years and many possible extensions of the MSSM have been proposed [4]. Even within the framework of MSSM, it was shown that the boundary condition at high energy which provides negative stop mass squared can reduce the fine tuning for the electroweak symmetry breaking [5] and explicit model has been proposed [6] [7].

As an extension of the MSSM, NMSSM (next to MSSM) is one of the most popular scenarios [8]. Gauge sector extensions also have been proposed [9] [10]. Recently BMSSM (beyond MSSM) has been proposed as a frame to study possible operators which can affect the Higgs sector [11]. There are extra fields above TeV scale but these new states can be integrated out below TeV such that we still keep the spectrum of the MSSM below TeV down to the weak scale. These new TeV particles modify the conventional Higgs potential and can increase the Higgs mass in this setup [11] and also Higgs mixing angle can be significantly changed such that Higgs phenomenology can be quite different from standard one [12]. Electroweak baryogenesis with the light stop in BMSSM has also been studied [13].

The LEP bound is applied to the SM Higgs and in principle it can be weaker in the MSSM, NMSSM or BMSSM if the production or decay is very different from the SM. There had been extensive studies on nonstandard decay of Higgs which can happen if there is an extra light particle (e.g., a singlet of NMSSM) and the decay of Higgs is not just $b\bar{b}$ [14].

In this Letter, we extend the work in the framework of BMSSM [12] which alters the Higgs phenomenology (both production and decay) significantly. We assume that all new states

other than the MSSM fields are heavier than TeV such that they are captured only through the effective higher dimensional operators after integrating out them. Thus the spectrum is the same as the MSSM below TeV. In this framework we propose a possibility of light Higgs which might have been produced at LEP I/II [15] [16] [17]. If CP odd Higgs (A) is lighter than Upsilon (bottomonium), it can alter Higgs decay significantly. In addition if light CP even Higgs (h) is lighter than Z boson such that $Z \to hA$ is kinematically allowed, $b\bar{b}$ produced from h decay can affect the electroweak precision data measured at LEP. In this case the suppression of $Z \to Zh$ is possible with the aid of BMSSM operators.

The contents of the Letter is following. Firstly, various Higgs search bounds are briefly reviewed to convince that light Higgs scenario proposed here is compatible with all the existing bounds. Secondly, we take the sample points of the BMSSM which have interesting features and can have interesting implications for the electroweak precision data of LEP. Thirdly, we attempt to soften the discrepancy between the SM predictions and the LEP precision measurements within the scenario. Finally, we summarize and conclude.

II. LEP HIGGS SEARCH BOUNDS

For the SM Higgs, LEP bound on the Higgs mass is 114 GeV at 95 percent confidence level (C.L.). This equally applies to the Higgs field which has the same coupling to Z boson and decays in the same way as the SM Higgs. Therefore, there are two ways to avoid the bound. If the production is suppressed, the bound becomes weaker. The modification of decay also makes the bound weaker depending on the channel. For the production, Higgsstrahlung is suppressed for light CP even Higgs if ZZh coupling is small. For $g_{ZZh}^2 = 0.04 g_{ZZh}^{2\ \mathrm{SM}}$, the Higgs can be as light as 70 to 75 GeV from decay mode independent search [18].

In this case the other CP even Higgs H couples to Z boson with almost the same strength as the SM Higgs since there is a sum rule, $g_{ZZh}^2 + g_{ZZH}^2 = g_{ZZh}^{2\ \mathrm{SM}}$. For H, we can modify its decay if CP odd Higgs decays mostly to AA rather than to $b\bar{b}$. If $Br(H \to b\bar{b}) \leq 0.2$ and $m_A < 10$ GeV (lighter than $2m_b$), H can be as light as 100 GeV as $H \to AA \to 4\tau$ does not give a strong constraint.

Once m_A is very light, we also expect the charged Higgs mass to be close to W boson mass in MSSM-like theories as the tree level mass relation between charged Higgs, CP odd

Higgs and W boson is following.

$$m_{H^\pm}^2 \; = \; m_W^2 + m_A^2. \tag{1}$$

This is violated by loop corrections in the MSSM but the violation is very tiny. In BMSSM, the modification can be sizable depending on which operators are added, but still the charged Higgs will be at around the weak scale. Such a light Higgs might be dangerous. However, it was shown that it can be perfectly consistent with the charged Higgs search from the top decay at the Tevatron since the charged Higgs decays not only to $\tau\nu$ (and cs) but also decays to $AW^{\pm *}$ [16].

If h and A production is kinematically allowed at the Z pole, it can provide a very interesting signature. For small ZZh coupling which is needed to keep h lighter than Z boson, ZAh coupling is almost maximal and hA associated production is possible. The branching ratio of Z to Higgs is typically a few percent of Z to $b\bar{b}$. There are two possibilities. If h mainly decays to AA, $Z \to hA \to 3A \to 6\tau$ puts a bound on h mass. If h is heavier than 70 GeV, the scenario is consistent with the current search bound. More interesting possibility is the case when h mainly decays to $b\bar{b}$. Although it requires a fine tuning in the parameter choice since h coupling to A is of order one while it couples to b with a bottom Yukawa coupling which is smaller than one except at large $\tan\beta$ ($\tan\beta \sim 60$). In this case, $Z \to hA \to b\bar{b}\tau^+\tau^-$ would be the main decay channel. For $m_h \geq 70$ GeV, h and A are produced with very small kinetic energy and two taus decayed from A would be very soft. Two tau jets carry about 15 GeV of energy (7.5 GeV each) and the measured energy of each tau jet will be typically smaller than 5 GeV since it emits at least one tau neutrino and can emit more in leptonic decays. If the energy of tau jet is less than 5 GeV, it is too soft to be identified as tau jet and the whole event will be recorded as hadron events.

In this Letter, we focus on the scenario in which $Z \to hA$ is kinematically allowed at the Z pole and h mainly decays to $b\bar{b}$. This happens for $m_h \sim 70$ GeV and $m_A \leq 2m_b$. To take into account the recent BaBar result on Upsilon decay, we take $m_A = 7$ or 8 GeV as a representative value. The change of m_A does not affect the result very much other than the light CP odd Higgs search bound.

III. BMSSM AND SAMPLE POINTS

The above mentioned scenario is hard to be realized in the MSSM. The eigenvalue of the light CP even Higgs is too small (less than 50 or 60 GeV) if CP odd Higgs mass is below 10 GeV in the MSSM. Also the light CP even Higgs usually couples more strongly to Z boson than the heavy one. Therefore, it is not possible to satisfy the direct search bound in the MSSM for such a light CP odd Higgs.

The scenario can be realized in the BMSSM if we include BMSSM operators. If there are new particles at around 1 TeV or higher and if they couple to Higgs fields with order one coupling, we can generate effective dimension five and dimension six operators which can give corrections comparable to the usual D term quartic couplings of Higgs fields. The BMSSM just adds new operators such that they can alter the mass and the couplings of the Higgs fields but does not introduce new light states into which Higgs can decay. Therefore, Higgs decay is modified in the BMSSM only through the modification of Higgs couplings, e.g., $h \to AA$.

There are many operators with effective dimension five and six in the BMSSM. In this Letter, we just consider two of them which might be relevant to the discussion. By including other operators, the whole parameter space would be expanded. Nevertheless, the main feature of the scenario would be the same.

The operators are

$$\begin{aligned}\delta V &= 2\epsilon_1 H_u H_d (H_u^\dagger H_u + H_d^\dagger H_d) + h.c. \\ &\quad + \epsilon_2 (H_u H_d)^2 + h.c. \\ &\quad + \epsilon_3 (H_u^\dagger H_u)^2 + \epsilon_4 H_u H_d (H_u H_d)^\dagger . \end{aligned} \tag{2}$$

ϵ_3 and ϵ_4 are real and ϵ_1 is assumed to be real to simplify the discussion. CP even Higgs mass matrix $\mathcal{M}^2$ is given as follows.

$$\begin{pmatrix} (M_Z^2 + 4v^2\epsilon_2)\cos^2\beta + m_A^2 \sin^2\beta + 4v^2\epsilon_1 \sin 2\beta & (-M_Z^2 - m_A^2 + 2\epsilon_4 v^2)\sin\beta\cos\beta + 4v^2\epsilon_1 \\ (-M_Z^2 - m_A^2 + 2\epsilon_4 v^2)\sin\beta\cos\beta + 4v^2\epsilon_1 & \{M_Z^2 + 2v^2(2\epsilon_2 + \epsilon_3)\}\sin^2\beta + m_A^2\cos^2\beta + 4v^2\epsilon_1 \sin 2\beta \end{pmatrix}.$$

ϵ_1, ϵ_2 and ϵ_4 are the operators that does not exist in the MSSM but can arise in the BMSSM after integrating out massive states at TeV and/or with supersymmetry breaking. ϵ_3 exists

already in the MSSM from top-stop loop but here we consider more general ϵ_3 which is not directly related to the stop mass. ϵ_3 can arise in the BMSSM if there is an extra U(1) and only H_u is charged under the extra U(1). We do not discuss the detailed BMSSM model beyond TeV. Instead we will focus on the effective operators. ϵ_1 affects both the diagonal elements and the off-diagonal elements. ϵ_2 enters only in the diagonal entries. ϵ_4 affects only the off-diagonal elements. The dependence of CP even Higgs mass on BMSSM parameters can be read off from the two by two matrix. The one in the diagonal elements can increase the eigenvalues if it is positive. On the other hand the cancelation in the off-diagonal elements can reduce the level repulsion such that the lightest eigenvalue can be larger than before. Thus as long as the light CP even Higgs mass is concerned, the role of ϵ_2 and ϵ_4 are almost the same.

Tree level mass of Charged Higgs is given by

$$m_{H^\pm}^2 = m_A^2 + m_W^2 + 2\epsilon_2 v^2 + \epsilon_4 v^2. \tag{3}$$

ϵ_1 and ϵ_3 does not affect the relation between m_A and $m_{H^\pm}$. Sizable corrections to the MSSM relation between m_A and $m_{H^\pm}$ are expected if ϵ_2 and/or ϵ_4 are sizable. As charged Higgs mass bound is stiff at around m_W, i.e., it can not be much lighter than W boson mass, ϵ_2 and ϵ_4 are expected to be positive if sizable. In the following discussion, we mainly focus on the effects of ϵ_1 and ϵ_2. The role of ϵ_4 is very similar to ϵ_2 as long as light CP even Higgs mass and charged Higgs mass are concerned. Only the impact on heavy CP even Higgs mass will be different and the phenomenological distinction is less clear. ϵ_3 is taken to be -0.1 in the following discussion. It can be achieved for very light stop or can be obtained with BMSSM operators. The origin of the operator is not the main concern of this paper.

Higgs spectrum is shown in Fig. 1. In the plots, the CP odd Higgs mass is chosen to be 7 GeV. A few GeV difference in m_A makes a little difference in CP even and charged Higgs mass spectrum. Two representative values of $\tan\beta$ (1.04 and 2) are chosen. When $\tan\beta$ is chosen to 1.04 (close to 1) (Fig. 1 (a)(b)(c)), the mass matrix of CP even Higgs has a special structure such that one of the eigenvalue is nearly constant (M_Z). The transition point appears when the off-diagonal element is almost canceled by ϵ_1. In the following discussion, we are interested in the region in which the off-diagonal element is positive after all. ($\epsilon_1 > 0.04$ in the plots.) Thus to reduce the light CP even mass to 80 GeV, we choose

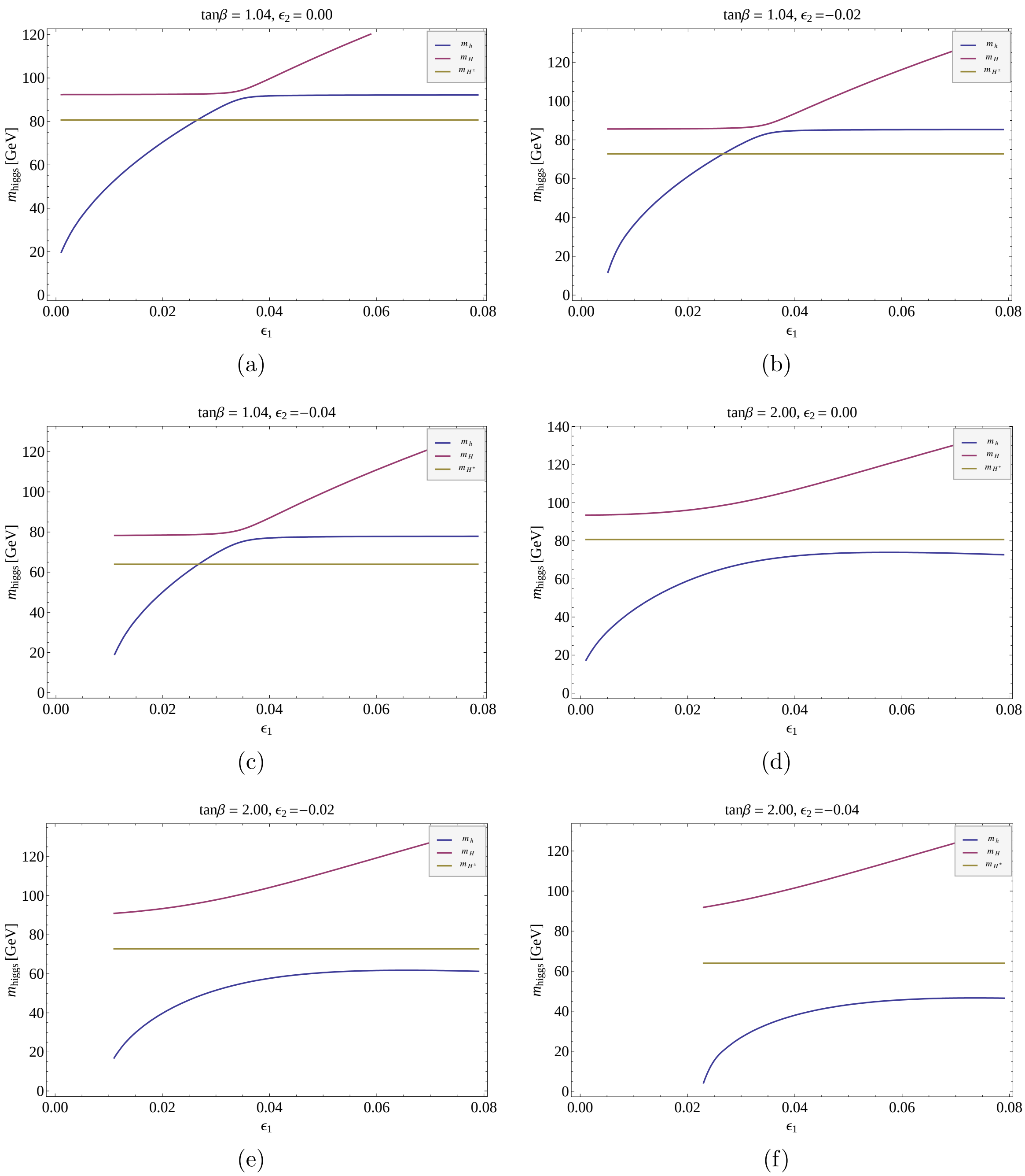


FIG. 1: Higgs spectrum scanned for ϵ_1 and ϵ_2 for several $\tan\beta$. $\epsilon_3 = 0.01$, $\epsilon_4 = 0$ and $m_A = 7$GeV are used here. Red, brown and blue lines denote $H, H^{\pm}$ and h, respectively.

ϵ_2 to be negative. $\epsilon_2 = -0.04$ provides the light CP even Higgs mass at around 80 GeV. However, in this case the charged Higgs turns out to be too light, 60 GeV, and the scenario is ruled out. When $\tan\beta = 2$ (away from 1), the spectrum shows a very smooth transition of the CP even Higgs mixing angle (α) from negative values ($\alpha < 0$) to positive ones ($\alpha > 0$).

The hAA and HAA couplings are modified with the presence of ϵ_1, ϵ_2 and ϵ_3. ($\epsilon_4 = 0$

from now on.)

$$
\begin{aligned}
g_{hAA} &= \lambda_0 \cos 2\beta \sin(\beta+\alpha) \\
&\quad -iv\left[-2\epsilon_1 \cos 2\beta \sin(\beta-\alpha) - \epsilon_2(3\cos(\beta-\alpha) - \cos 2\beta \cos(\beta+\alpha)) + 4\epsilon_3 \cos^2\beta \sin\beta \cos\alpha\right], \\
g_{HAA} &= -\lambda_0 \cos 2\beta \cos(\beta+\alpha) \\
&\quad -iv\left[2\epsilon_1 \cos 2\beta \cos(\beta-\alpha) - \epsilon_2(3\sin(\beta-\alpha) + \cos 2\beta \sin(\beta+\alpha)) + 4\epsilon_3 \cos^2\beta \sin\beta \sin\alpha\right],
\end{aligned}
$$

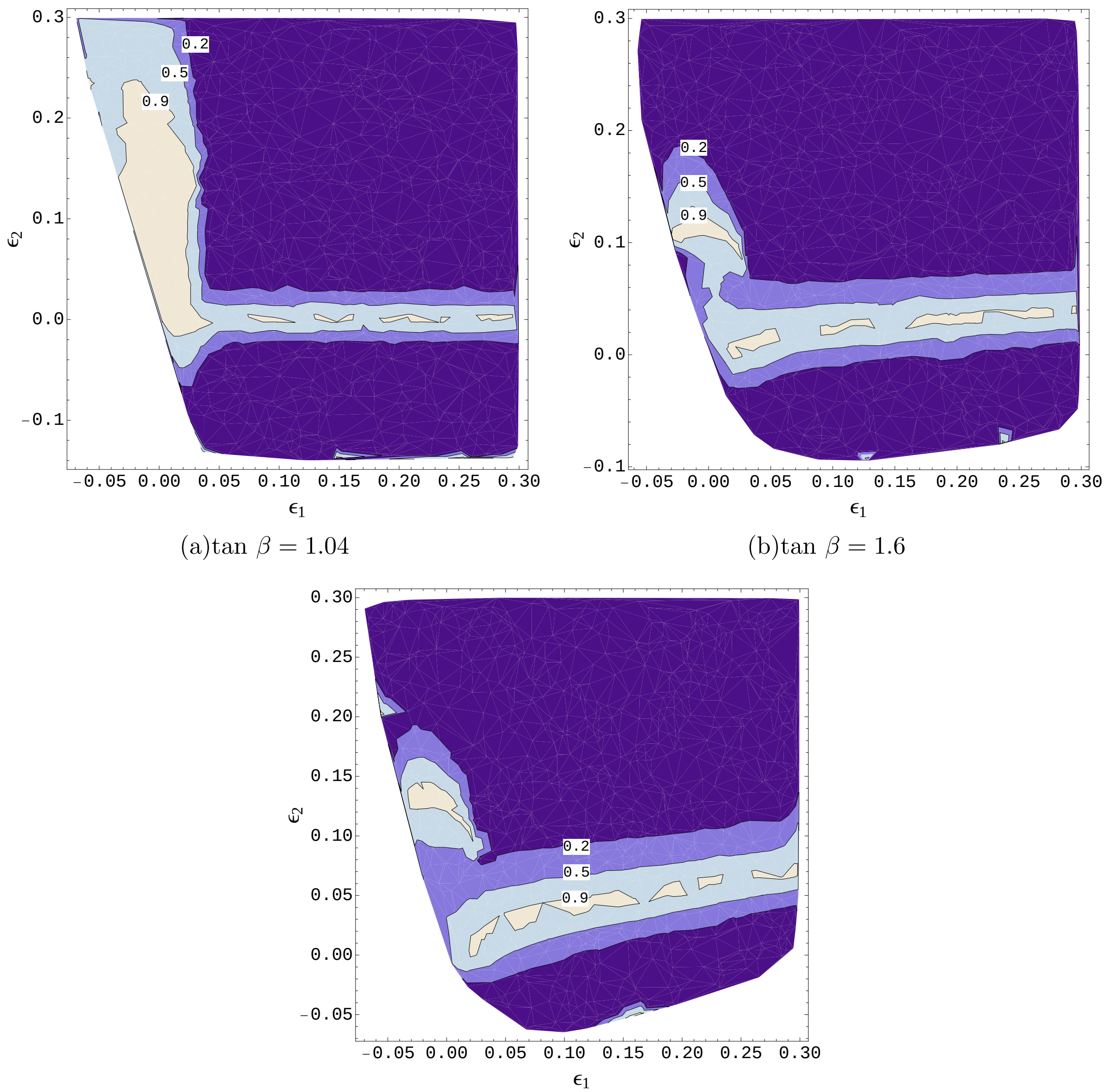
where $\lambda_0 = -iM_Z^2/v$.

The corrections to the masses and couplings from ϵ_1 and ϵ_2 are also discussed in [19]. It is clear that $h \to AA$ dominates over $h \to b\bar{b}$ in most of parameter space. Nonetheless, there is a chance that $h \to AA$ can be suppressed compared to $h \to b\bar{b}$ since $h \to b\bar{b}$ is given by bottom Yukawa coupling alone (dominantly) while $h \to AA$ is given by two or three independent contributions. It is this cancelation which we will use to explain the forward backward asymmetry of bottom quark later in this paper.

Fig. 2 shows the ratio of partial decay width $\Gamma(h \to b\bar{b})/(\Gamma(h \to b\bar{b}) + \Gamma(h \to AA))$ for $\tan\beta = 1.04, 1.6$ and 2, respectively. This is basically the branching ratio of $h \to b\bar{b}$ as $b\bar{b}$ and AA provide dominant decay channels. $\mathrm{Br}(h \to b\bar{b})$ is larger than 50% in the skyblue and ivory regions. When $\tan\beta = 1.04$, it is possible to have a cancelation of ϵ_1 and ϵ_2 contribution to g_{hAA} coupling and there appears a bulk region in between $\epsilon_1 = 0$ and 0.05. The horizontal line with $\epsilon_2 \sim 0$ in Fig. 2 (a) shows that ϵ_1 dependence on g_{hAA} almost vanishes since $\cos 2\beta \sim 0$. In other plots, the cancelation appears as a line in ϵ_1 and ϵ_2 plane and sizable $\mathrm{Br}(h \to b\bar{b})$ is possible along the line.

Assuming that the conditions is satisfied ($h \to b\bar{b}$ dominates over $h \to AA$), we can compare how much of $b\bar{b}$ pairs can be produced from LEP compared to the ones directly produced from Z boson decay. $\mathrm{Br}(Z \to hA \to b\bar{b})$ depends on light CP even Higgs mass and CP odd Higgs mass because the most significant factor is the kinematic suppression at the Z pole. A decays into soft 2τ or $c\bar{c}$ and we assume these soft jets are not tagged.

Fig. 3 shows the ratio of bottom quark events produced from Higgs compared to those from Z. Here $Z \to Zh$ is assumed to be zero and $Z \to hA$ coupling is maximized. Also $\mathrm{Br}(h \to AA)$ is taken to be 1. For $m_h = 75$ GeV, the ratio can be about 0.5 % and if it is lighter, $m_h = 70$ GeV, it can be as large as 1%. The direct search limit from the LEP allows



(a)tan $\beta = 1.04$

(b)tan $\beta = 1.6$

(c)tan $\beta = 2$

FIG. 2: Branching ratio to $b\bar{b}$, $\frac{\Gamma(h\to b\bar{b})}{\Gamma(h\to b\bar{b})+\Gamma(h\to AA)}$ is plotted on (ϵ_1, ϵ_2) space. $\epsilon_3 = 0.01$, $\epsilon_4 = 0$ and $m_A = 7$GeV are taken here. At each point on the curves, Higgs mass may vary with respect to $\epsilon_{1,2}$.

the light CP even Higgs as light as 72 GeV[20].

In this section it is shown shown that the new parameter space of BMSSM allows light Higgs scenario. CP odd Higgs mass is about 7 or 8 GeV (lighter than $2m_b$) and light CP even Higgs is about 70 to 75 GeV which avoiding model independent search bound from OPAL by having small ZZh coupling. There are two consequences of this scenario. One is that on-shell hA production is possible at the Z pole and there is a possibility that we

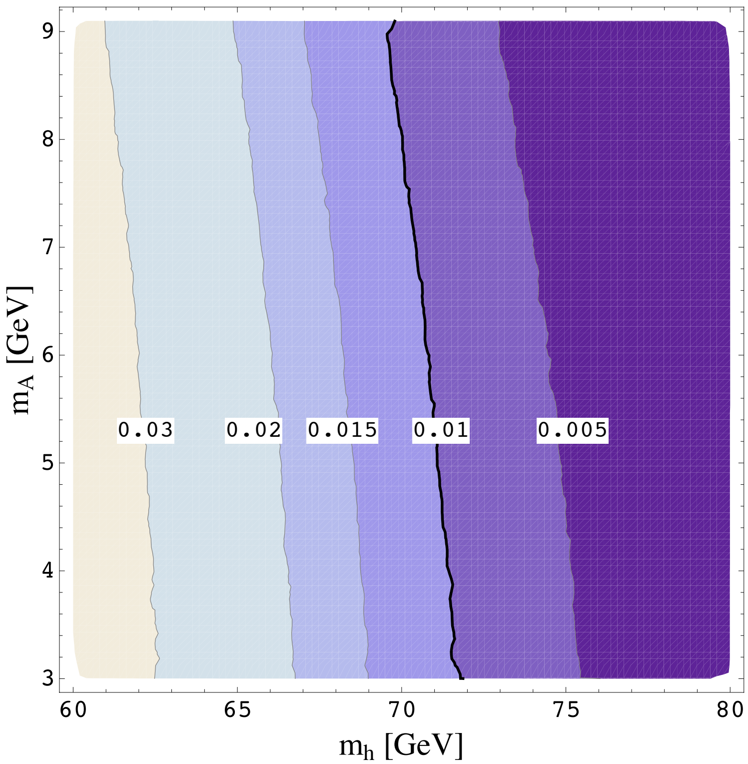


FIG. 3: The ratio of bottom quark pair produced from Higgs vs Z, $\sigma(e^+e^- \to hA \to b\bar{b})/\sigma(e^+e^- \to Z \to b\bar{b})$, is plotted on (m_h, m_A) space.

are faked to believe that all the bottom quark pairs are from Z decay even in the case h decays into $b\bar{b}$. This might cause an immediate contradiction with the observation of R_b consistent with the SM prediction. However, it remains as a perfect possibility here since the other consequence of the scenario can reconcile it. The scenario predicts a very light charged Higgs, $m_{H^\pm} \sim m_W$. For such a light charged Higgs, $Z \to b\bar{b}$ vertex gets a correction of order 1% and it is consistent with new contributions from $Z \to hA \to b\bar{b}$. Also such a light charged Higgs is not ruled out by current experimental bounds since $H^\pm \to W^* A$ can have a sizable branching ratio while the standard bound is given with the assumption that $H^\pm \to \tau\nu$ (or $H^\pm \to c\bar{s}$) is the dominant decay mode [16] [17]. In the following sectioin we review the status of LEP electroweak precision data and discuss the implication of this new scenario on LEP data. All the discussion in this section can also be considered in the context of two Higgs doublet model (2HDM) as 2HDM is a generalization of BMSSM as long as Higgs sector is concerned.

IV. LEP ELECTROWEAK PRECISION DATA : A^b_{FB} AND R_b

LEP experiment is known as one of the most successful ones which confirm the Standard Model (SM) at a very high precision, one per mil. This acts as the main source of the frustration for any physics beyond the SM. In this paper we take a viewpoint that 3 sigma deviation of $A^b_{\rm FB}$ between the prediction and the measurement existing in LEP data might be a hint for a new physics. We discuss whether light Higgs scenario might be relevant to reduce the tension.

Forward-backward asymmetry of bottom quark produced from electron-positron pair,

$$A^b_{\rm FB}(M_Z) = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{4} A_e A_b \tag{4}$$

$$= \frac{3}{4} \frac{((g^e_L)^2 - (g^e_R)^2)}{((g^e_L)^2 + (g^e_R)^2)} \frac{((g^b_L)^2 - (g^b_R)^2)}{((g^b_L)^2 + (g^b_R)^2)}. \tag{5}$$

has been measured at LEP I and LEP II and it is the electroweak observable which shows the largest discrepancy compared to the standard model prediction:

$$A^b_{\rm FB} = 0.0992 \pm 0.0016, \tag{6}$$

$$A^b_{\rm FB\ SM} = 0.1037 \pm 0.0008. \tag{7}$$

The difference 0.0045 corresponds to 2.8σ deviation with the experimental error or 2.5σ deviation with the combined error. The strong constraints on the bottom quark pair production at the Z pole from R_b measurements makes hard to resolve this deviation.

$$R_b = \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to \text{hadrons})} = \frac{((g^b_L)^2 + (g^b_R)^2)}{\sum_q ((g^q_L)^2 + (g^q_R)^2)}, \tag{8}$$

where q represents five quarks excluding top quark. The observed value and the standard model prediction agrees well:

$$R_b = 0.21629 \pm 0.00066, \tag{9}$$

$$R_b{}^{\rm SM} = 0.2158. \tag{10}$$

Now the difference 0.0005 corresponds to 0.7σ.

The discrepancy of R_b is 0.3%, but the difference in $A_{\rm FB}^b$ is about 4.4% - which is more than ten times larger than that of R_b. Any new physics responsible for the deviation of $A_{\rm FB}^b$ should preserve the branching ratio of $Z \to b\bar{b}$ with a high precision. If g_L^b and g_R^b were comparable in size, the total sum could be preserved by modifying g_L^b and g_R^b at a percent level with the opposite direction. However, in reality, the tree level value is

$$g_L^b = -\frac{1}{2} + \frac{1}{3}\sin^2\theta_W \simeq -0.42, \tag{11}$$

$$g_R^b = \frac{1}{3}\sin^2\theta_W \simeq 0.08, \tag{12}$$

where the left-handed contribution is about 27 times larger. In general it is possible for a left-handed coupling to obtain a percent level correction from a loop but to keep the branching ratio to be the same, we need about 25 percent correction to right-handed coupling g_R^b. Without significant modification of the right-handed coupling, the loop correction to the left-handed coupling is typically negative (from charged Higgs) and make it impossible to keep R_b as it is.

If the charged Higgs is very light (lighter than 100 GeV) and $\tan\beta$ is close to 1, the (B)MSSM correction to $Z \to b\bar{b}$ can be sizable such that $R_b^{\rm SM}$ can be reduced by 0.5%, 1% or 1.5% [25].

Light supersymmetric particles can cancel the charged Higgs loop. Fig. 4 shows $R_b^{\rm BMSSM}$ which also includes light stop. For $\tan\beta = 1.5$, the predicted $R_b^{\rm BMSSM} = 0.2150$ which is about 0.7 % smaller than the measured value.

The correction appears in g_L and it is impossible to make a sizable correction to g_R (27 times larger one compared to g_L) from loop corrections to keep R_b as it is. Such modification of g_L, g_R is not required if there are new processes which gives fake $Z \to b\bar{b}$ signals. In light Higgs scenario of BMSSM, $Z \to hA \to 2b + (2\tau \text{ or } c\bar{c})$ can be counted as $Z \to 2b + gluons$ events when tau jets are soft, because it is hard to distinguish soft tau jets from QCD backgrounds.

In this case, measured R_b value should be compared to $R_b^{\rm BMSSM\ total} = R_b^{\rm BMSSM} + R_b^{\rm fake}$

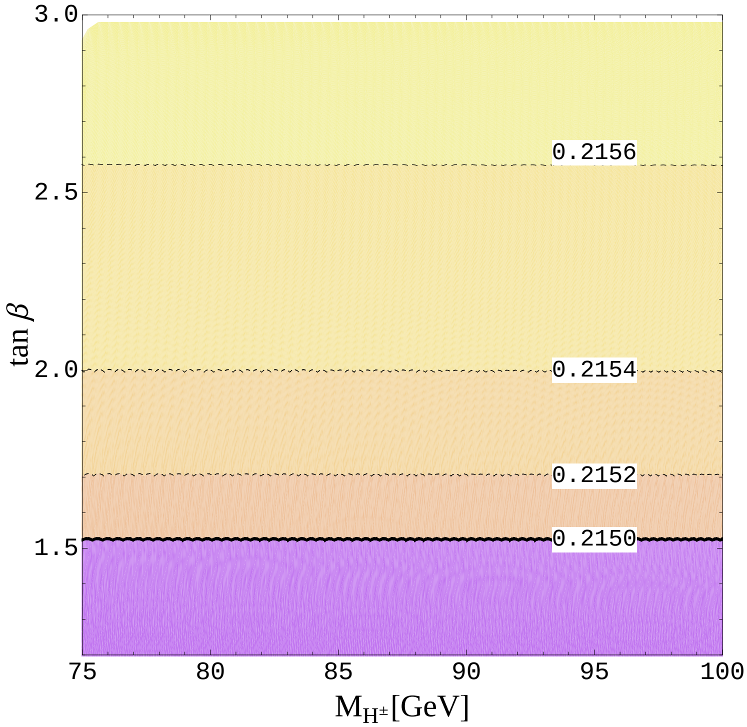


FIG. 4: $R_b^{\rm BMSSM}$ values from loop correction of charged Higgs and SUSY. $m_{\tilde{q}_3} = m_{\tilde{t}} = 190$GeV, $A_t = \mu = 200$GeV. This is calculated by our own code using formulae of [25].

and measured $A^b_{\rm FB}$ becomes

$$A^b_{\rm FB} \;=\; \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B + \sigma_{fake}}. \tag{13}$$

Because Higgs is a scalar particle, it evenly contributes to σ_F and σ_B, so it decreases $A^b_{\rm FB}$. BMSSM has a parameter space such that prediction of R_b is sufficiently smaller than R_b^{SM} so $\sigma_{\rm fake}$ ($R_b^{\rm fake}$) can be large enough, a sizable loop correction to g_R^b is not required.

However, it is not clear how many of the events will be included in data set for $A^b_{\rm FB}$. To measure $A^b_{\rm FB}$, the direction of bottom quarks is required. Events which contain hard initial state radiation(ISR) photons or final state radiation(FSR) gluons should be removed because it disturbs the direction of beam or bottom quarks. For example, OPAL uses combination of sphericity([22]), total energy, energy imbalance along the beam direction([23]) and so on, to select such hadronic decay events. In $Z \to hA \to 2b(2\tau \;\text{ or }\; c\bar{c})$ events, angle between $\tau(c)$ and b can be large because two jets are loosely correlated. In this case, tau jets can look like hard gluon jets from b-quarks, so it might be rejected by the selection cut of $A^b_{\rm FB}$.

To make the discussion simple, we assume $\text{Br}(h \to b\bar{b}) = 1$ and $\text{Br}(A \to \tau^+\tau^-) = 1$. Also

we assume that all the events of $Z \to hA$ are recorded as $Z \to b\bar{b}$ due to the softness of tau jets. The exact fraction of events which is included in $A^b_{\rm FB}$ needs a detailed information of the events. Here we consider the most optimistic case in which all the events generated from $Z \to hA$ are included in $A^b_{\rm FB}$ measurement. Thus the estimation here would work as the maximum correction we can expect from this scenario.

$$R_b \;=\; \frac{\Gamma(Z\to b\bar{b})+\Gamma(Z\to hA)}{\Gamma(Z\to \text{hadrons})+\Gamma(Z\to hA)}. \tag{14}$$

Let $a = \frac{\Gamma(Z\to hA)}{\Gamma(Z\to b\bar{b})}$. For very small $a \ll 1$,

$$R_b \;=\; \frac{\Gamma(Z\to b\bar{b})}{\Gamma(Z\to \text{hadrons})}\left(1+(1-R_b)a\right). \tag{15}$$

Therefore, if one loop correction decreases $(g^b_L)^2$ by one percent, R_b remains to be the same if $a = 0.012$. When there is no change in $(g^b_L)^2$, $a = 0.012$ will increase R_b by one percent which is the correction allowed by 2σ of R_b measurement. Total Z width is precisely measured and should be kept within 0.1%. $a = 0.012$ gives 0.15% increasement of total Z width which is in 1.5σ range.

The same a enters in $A^b_{\rm FB}$ ($A^b_{\rm FB} = \frac{3}{4}A_e A_b$).

$$A_b \;=\; \frac{\Gamma(Z\to b_L\bar{b_L})-\Gamma(Z\to b_R\bar{b_R})}{\Gamma(Z\to b_L\bar{b_L})+\Gamma(Z\to b_R\bar{b_R})+\Gamma(Z\to hA)} \tag{16}$$

$$\;=\; \left(\frac{\Gamma(Z\to b_L\bar{b_L})-\Gamma(Z\to b_R\bar{b_R})}{\Gamma(Z\to b_L\bar{b_L})+\Gamma(Z\to b_R\bar{b_R})}\right)(1-a). \tag{17}$$

Therefore, $a = 0.012$ will reduce A_b (and thus $A^b_{\rm FB}$) by 1.2% which will make the difference between the prediction to be 0.0033 which is within 2 σ (1.8 σ). Here we simply assumed that hA production is isotropic and appears only in the denominator and cancels in the numerator. Whether $1-a$ is the right dependence depends on the fitting method of angular distribution. The actual change to A_b from a can be smaller than what is estimated here. Note that changing g^b_L can not change A_b very much since it dominates in the numerator and denominator at the same time.

V. FLAVOR CHANGING NEUTRAL CURRENTS : $b \to s\gamma$

It might be challenging to explain $b \to s\gamma$ with $m_H^{\pm} = 80$ GeV as the lower mass bound on the charged Higgs is about 250 GeV if only the charged Higgs contribution is taken into account. In the MSSM, light stop is also natural and can be responsible for the cancelation of charged Higgs contribution. 2 σ range of $b \to s\gamma$ is obtained from the cancelation of the charged Higgs loop with the stop-chargino loop.

At first glance, $b \to s\gamma$ observable is not dramatically changed in BMSSM framework. The reason is that Higgs sector, especially Higgs cubic and quartic couplings, suffers from considerable modification but chargino and squark sectors do not. However, such BMSSM operators can modify higgsino operators and then modify chargino and neutralino mixing. Futhermore, squark mixing is also changed by superpotential modification by ϵ_1 operator. In most natural case, stop and chargino masses are also as light as Higgs masses, and small modification to Higgsino sector could be important for $b \to s\gamma$ observable. BMSSM modification to chargino sector is given in chargino mass matrix

$$X = \begin{pmatrix} M_2 & \sqrt{2}M_W \sin\beta \\ \sqrt{2}M_W \cos\beta & \mu \end{pmatrix} + \frac{\epsilon_1}{\mu} v^2 \sin 2\beta \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}. \tag{18}$$

Stop mass matrix is given by

$$m_{\tilde{t}}^2 = \begin{pmatrix} m_{Q_3}^2 + m_t^2 + \Delta_u & m_t(A_t - \mu\cot\beta) \\ m_t(A_t - \mu\cot\beta) & m_{\bar{u}_3}^2 + m_t^2 + \Delta_{\bar{u}} \end{pmatrix} - 2m_t \frac{\epsilon_1}{\mu} v^2 \cos^2\beta \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}. \tag{19}$$

Consequently, chargino and stop mixing matrices are also changed. ϵ_1 term changes supersymmetric μ term as

$$\mu \to \mu + \frac{\epsilon_1}{\mu} v^2 \sin 2\beta. \tag{20}$$

Therefore, we can have effectively large higgsino mass and large stop mixing for small $\tan\beta$ case in which we are interested. If $M_2 \sim \mu \sim 100$GeV and $\epsilon_1 \sim 0.1$, supersymmetric μ term can be enhanced 20-30% for $1 \lesssim \tan\beta \lesssim 2$ and then ϵ_1 contribution could modify $b \to s\gamma$ observable. Numerical result is shown in fig. 5.

The thick black line at 4.7×10^{-4} is the 2 σ bound. Only the left part from the thick black line is consistent with the measured branching ratio of $b \to s\gamma$. In this case the lightest

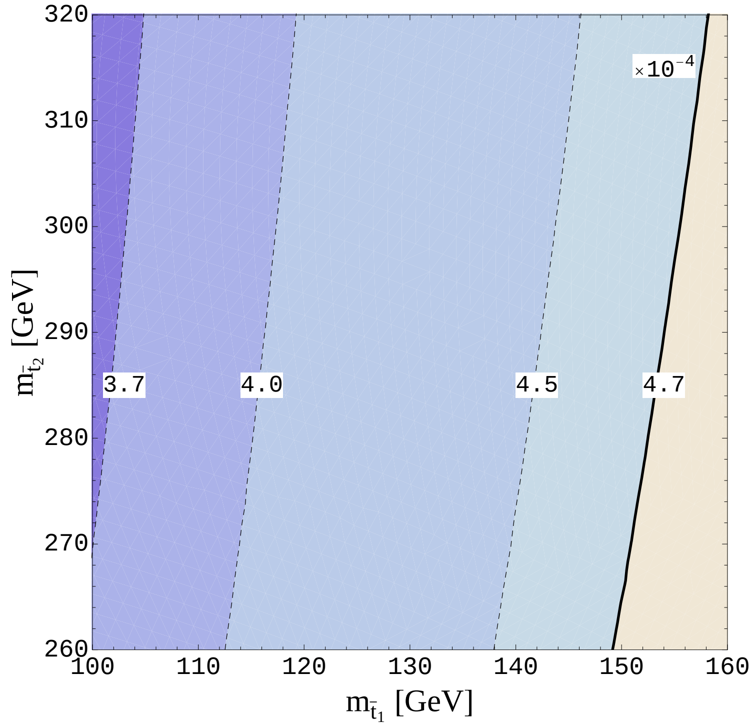


FIG. 5: This is contour plot of Br($b \to s\gamma$) for $M_2 = 200$GeV, $\epsilon_1 = 0.0096$, $\epsilon_2 = 0.00086$, $2\epsilon_3 v^2 \sin^2\beta = 708\text{GeV}^2$ and $\tan\beta = 1.9$. This is calculated by SuperIso v2.3[24]

stop mass should be less than 160 GeV which is certainly lighter than the top quark. It is generally the case for different choice of $\tan\beta$ and other supersymmetry breaking parameters. Wino/higgsino mass also should be light since large loop corrections due to small $\tan\beta$ and light charged Higgs have to be canceled by supersymmetric counter terms (stop-chargino loop) which can be sizable when stop and chargino are light enough. This provides an interesting connection between our scenario and the electroweak baryogenesis which works only when the right-handed stop is lighter than top quark. The detailed study of the implication of BMSSM operators to $b \to s\gamma$ and muon $g-2$ will be given elsewhere [26].

VI. CONCLUSION

In this paper we explored the phenomenology of light Higgs scenario in BMSSM. More specifically, we found that h and A production at the Z pole is kinematically allowed in BMSSM. For very light A ($\leq$ 10 GeV) and h slightly lighter than Z ($\sim$ 70 GeV) which is still consistent with the LEP data, h and A are produced with small momentum. Bottom quark pairs produced from h are close to back to back and tau pairs from A are soft enough.

Forward backward asymmetry or R_b measurement at LEP can be affected by bottom quarks produced from Higgs. For $\tan\beta \sim 1.5$ to 2, it is possible to find a parameter space which can ameliorate the tension in $A^b_{\rm FB}$ without spoiling nice agreement in R_b.

This scenario at the same time predicts very light charged Higgs $m_{H^\pm} \sim m_W$ but still it can be consistent with current $b \to s\gamma$ observation by having a cancelation with light stop-chargino loop. To confirm whether this is the case or not, more careful analysis on discriminating soft taus from gluon jets and angular distribution fit is needed. Independently of its relation to $A^b_{\rm FB}$, light CP odd Higgs scenario in BMSSM or 2HDM is interesting enough and further exploration is left for future work.

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